Acceleration of particles in pulsar magnetosphere and the X-ray radiation

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Abstract

The available data of single X-ray pulsars, their wind nebulae, and the SNRs which are connected to some of these sources are analysed. It is shown that electric field intensity of neutron stars tears off charged particles from the surface of neutron star and triggers the acceleration of particles. The charged particles are accelerated mainly in the field of magnetodipole radiation wave. Power and energy spectra of the charged particles depend on the strength of the magnetodipole radiation. Therefore, the X-ray radiation is strongly dependent on the rate of rotational energy loss and weakly dependent on the electric field intensity. Coulomb interaction between the charged particles is the

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main factor for the energy loss and the X-ray spectra of the charged particles.

Key words: Pulsar, PWN, X-ray

1 Introduction

The number of single X-ray pulsars and the radio pulsars which have been detected in X-ray with characteristic time (τ) up to 10^6 yr located at distances less than 7 kpc from the Sun together with 2 pulsars in Magellanic Clouds is 33. These pulsars have been observed in 0.1-2.4 keV band (Becker & Trumper 1997; Becker & Aschenbach 2002) and in 2-10 keV band (Possenti et al. 2002) and all the available data have been collected, revised and put together in Table 1. All of these pulsars have rate of rotational energy loss $\dot{E}>3\times10^{34}$ erg/s. Nine of these 33 pulsars are connected to F-type supernova remnants (SNRs) and 8 of them are connected to C-type SNRs. Therefore, there exist pulsar wind nebulae (PWNe) near these 17 pulsars which are located at d<7 kpc. Three pulsars are connected to S-type SNRs and 3 other pulsars are connected to SNRs for which the morphological type is not known. Ten pulsars with detected X-ray radiation are not connected to SNRs and 6 of them have characteristic ages $2\times10^5<\tau<10^6$ yr. Among the 33 pulsars, 2 of them are X-ray pulsars from which radio radiation has not been observed and they are connected to SNRs (pulsar J1846-0258 to SNR G29.7-0.3 and pulsar J1811-1925 to SNR G11.2-0.3). Radio pulsar J1646-4346 (d=4.51 kpc) which is connected to C-type SNR G341.2+0.9 but not observed in X-ray is also included in the list. Apart from these sources, we have also included 14 radio pulsars with $\dot{E}>4\times10^{35}$ erg/s, $\dot{P}>10^{-15}$ s/s and d$\leq$7 kpc in Table 1. Also, 6 single millisecond pulsars from which X-ray radiation have been observed are displayed in Table 1.

The main aim in this work is to analyse the conditions which are necessary for the acceleration of relativistic particles, the X-ray radiation produced in the magnetospheres of pulsars and their PWNe.

2 Dependence of the ejection of relativistic particles on different parameters of pulsars

As known, very young pulsars have the capability to eject relativistic particles. Power and spectra of particles must be related to different parameters of pulsars, particulary to the induced electric field intensity of which it is practically impossible to find the exact expression, because there are large uncertainties in the magnetic field structures of neutron stars in plasma. Therefore, we use the simplified relation

$$E_{el} = \frac{B_r R}{P} \tag{1}$$

(Lipunov 1992). Here, R is the radius, B_r is the real value of the magnetic field intensity on the pole, P is the spin period of the neutron star and c is the speed of light. Naturally, number and energy spectra of relativistic particles also depend on the conditions in the atmospheres of neutron stars (density and temperature). Independent of the mechanism, the rate of rotational energy loss ($\dot{E}$) depends only on the moment of inertia (I), the spin period and the time derivative of the spin period ($\dot{P}$)

$$\dot{E} = \frac{4\pi^2 I \dot{P}}{P^3}. \tag{2}$$

If we assume that practically the rate of rotational energy loss is connected only to magnetodipole radiation (Lipunov 1992; Lyne & Graham-Smith 1998), then the value of the effective magnetic field $B=B_r$ and

$$\dot{E} = \frac{2}{3}\frac{\mu^2\omega^4}{c^3} = \frac{32\pi^4}{3c^3}\frac{B^2R^6}{P^4} \tag{3}$$

where μ is the magnetic moment of neutron star. From expressions (1) and (3) we get

$$\dot{E} = \frac{2\pi^2}{3c}\frac{R^4}{P^2}E_{el}^2. \tag{4}$$

As seen from this equation, $\dot{E}$ is directly proportional to ${E_{el}}^2$ and inversely proportional to P^2.

From expressions (1)-(3), we can get

$$E_{el} \sim I^{1/2}R^{-2}\tau^{-1/2} \tag{5}$$

from which it follows that the lines of E_{el}=constant roughly pass parallel to the lines of τ=constant on the P-$\dot{P}$ diagram (where I and R are assumed to be constant). Dependences of τ, E_{el}, B, and $\dot{E}$ on the values of I, R, and the braking index (n) and also the evolutions of pulsars with very different parameters are examined in detail by Guseinov et al. (2003a).

The existing theories do not give us the possibility to estimate the value of the voltage better than the order of magnitude. But it is exactly known that charged particles can be pulled out from the hot atmosphere of pulsar because of the large value of E_{el} and they can be accelerated. Further acceleration can take place in the field of the magnetodipole wave (Lipunov 1992). Which of these mechanisms is mainly responsible for the acceleration must be determined from the observational data. It may be the case that the voltage creates only basis for further acceleration of particles similar to the case of the Maxwell tail of hot particles (or particles which have already been accelerated with some other mechanism) in the shock fronts of SNRs. In the regular acceleration models (Bell 1978a, 1978b, Krymsky 1977), the further acceleration of particles with high energy takes place under the crossing through the shock fronts of SNRs (Allakhverdiev et al. 1986). Therefore, it is necessary to analyse the observational data.

3 How are the observational data related to the theoretical idea?

From the observations of the radio and X-ray radiation of neutron stars with power-law spectra (excluding the cooling radiation of neutron stars), there is direct evidence for continuing particle acceleration. Such X-ray radiation have been observed, for example, from pulsars J1856+0113 and J1801-2451 which have PWNe and have values of $\dot{E}\sim(4\text{-}5)\times10^{35}$ erg/s and 2.5×10^{36} erg/s, respectively. On the other hand, millisecond pulsars J1939+2134 and J1824-2452 with $\dot{E}\sim(1\text{-}2)\times10^{36}$ erg/s also have similar X-ray radiation as the previous pulsars. As seen in Table 1, these pulsars, beginning from J1856+0113, have values of X-ray radiation 10^{33}, 1.5×10^{33}, 5×10^{32}, and 3.6×10^{33} erg/s, respectively, in the 2-10 keV band (Possenti et al. 2002; Becker & Aschenbach 2002). We have estimated the ratio $(\frac{\dot{P}}{P})^{1/2}\sim\tau^{-1/2}$ from the dependence of E_{el} (see expression (5)) for pulsars J1856+0113, J1801-

2451, J1939+2134, and J1824-2452 and we have found the values 9×10^{-7}, 10^{-6}, 7×10^{-9}, and 3×10^{-8} $s^{-1/2}$, respectively. If in all these four cases the values of radius and moment of inertia of the pulsars are approximately the same, then the values of the electric field intensity may also have approximately the same ratios.

In Figure 1, dependence of the X-ray luminosity in 2-10 keV band ($L_{2-10keV}$) on the value of $\dot{E}$ for the single pulsars with distances up to 5 kpc from the Sun together with 2 pulsars in the Magellanic Clouds (see Table 1) is represented. As seen in Figure 1, pulsars J1856+0113 and J1801-2451 have $\dot{E}$ values similar to single millisecond pulsars J1824-2452 and J1939+2134, and their $\dot{E}$ values are more than 300 times greater than their X-ray luminosities in 2-10 keV band. Therefore, the luminosity of the power-law X-ray radiation (which includes the radiation of the relativistic particles in the Coulomb and magnetic fields) mainly depends on the value of $\dot{E}$. How can this approach be confirmed also for other pulsars based on the observational data?

Since we are interested in the acceleration of particles, we have chosen the pulsars for which $L_{2-10keV}/L_{0.1-2.4keV}>1$, so that, we avoid the errors connected to the interstellar absorption and the radiation related with the cooling of neutron stars. As seen from Table 1, these conditions are not satisfied for the last 4 pulsars with log τ=9.58-9.86 which are also displayed in Figure 1. But they are very close to the Sun and very old, therefore they do not create any difficulties. All the young pulsars shown in Figure 1 have not only hard spectra but also have PWNe. As seen from the equation of the best fit

$$L_{2-10keV} = 10^{-19.46\pm3.32}\dot{E}^{1.45\pm0.09} \tag{6}$$

there exists well a dependence between $L_{2-10keV}$ and $\dot{E}$ for which the radiation is related with the accelerated particles.

In Figure 2, the relation between $L_{2-10keV}$ and the characteristic time of the same pulsars shown in Figure 1 is represented. As seen from the figure, a single dependence for both the young and the old pulsar populations does not exist (see also Possenti et al. 2002). Pulsars with similar values of $L_{2-10keV}$ and $\dot{E}$ may have very different values of characteristic time and this leads to different dependences for each population. As their ages increase, the young pulsars continue to move practically along the same direction on the L_x-τ diagram. Therefore, the electric field intensity does not determine the intensity and maybe also the spectra of the relativistic particles. These

mainly depend on the value of $\dot{E}$, whereas, large values of E_{el} mainly trigger the acceleration of particles.

As seen from Figure 1 and expression (6), as $\dot{E}$ decreases the X-ray luminosity of pulsars also decreases. So, in order to have the probability to observe X-ray radiation from a pulsar to be high for a fixed value of E_{el}, the P value of the pulsar must be small (see expression (4)). On the other hand, as seen from Figure 1 and Table 1, the L_x values of the young pulsars which are connected to SNRs are $\sim$5 orders of magnitude larger than the L_x values of old ms pulsars and this is also seen from expression (6). This must be the result of small number of relativistic and non-relativistic charged particles in the magnetospheres of ms pulsars.

As seen from Figure 2, the difference in the τ values of very old ms pulsars (τ>10^9 yr) and young pulsars is about 5.5 orders of magnitude (and from expression (5) the difference in the ${E_{el}}^2$ values is also about 5.5 orders of magnitude). The differences in the $\dot{E}$ values is about 3-3.5 orders and in the P values is on average 2.5 orders of magnitude. Considering that the expression for E_{el} can only roughly be determined as mentioned above, these data show that the relation between $\dot{E}$, E_{el} and P in expression (4) is valid.

In order to tear off particles from the surface of neutron star it is necessary to have large values of E_{el}. The occurence of this process must be easier under the existence of hot and extended atmosphere. Therefore, the values of mass and age of pulsars must also have important roles in the formation of the X-ray emission.

If the braking index n is constant along all the evolutionary tracks, then the age of the pulsar is

$$t = \frac{P}{(n-1)\dot{P}}(1-(\frac{P_0}{P})^{n-1}) = \tau \times (1-(\frac{P_0}{P})^{n-1}). \qquad (7)$$

For the young pulsars P_0 (the initial spin period of pulsar) can be assumed to be much less than P, so that, τ can approximately be equal to the age. For recycled ms pulsars, the P value can be comparable to the P_0 value (the period which the radio pulsar is born with), so that τ can be several times larger than the age. For our purposes such a difference is not significant since it is enough to know the order of magnitude of the age which is much longer than the cooling time.

As the last 4 pulsars displayed in Table 1 with $\dot{E}$ values close to 3×10^{33} erg/s can emit X-ray, all of the single old ms pulsars with $\dot{E}$>3×10^{33} erg/s

must also have X-ray radiation. On the other hand, all the 5 old ms pulsars with P$\leq$6 ms which are located up to $\sim$0.5 kpc (ATNF 2003; Guseinov et al. 2002) have been detected in X-ray (Possenti et al. 2002; Becker & Aschenbach 2002). Since the number density of old ms pulsars is very large compared to the number density of low mass X-ray binaries, the ages of these pulsars must not be much less than τ in general. As we see, although the recycled millisecond pulsars are very old, they still emit X-ray because they have large $\dot{\rm E}$ values.

The X-ray luminosities of pulsars together with their PWNe are represented in Table 1. Often, such X-ray luminosity values include both the X-ray radiation coming from the pulsar and the PWN together, because it is difficult to separate the emission of the pulsar from the emission of the PWN. Therefore, the radiation of single ms pulsars must be smaller compared to single young pulsars for equal values of $\dot{\rm E}$. This must be true also because of young pulsars having large values of electric field intensity and possibly sometimes having smaller masses. Therefore, it is strange that ms pulsar J1824-2452 has larger luminosity compared to young pulsar J1801-2451 (see Figure 1). Actually, the uncertainties in the luminosity values of these ms pulsars may be large.

In Figure 3, P-$\dot{\rm P}$ diagram of all the pulsars in Table 1, which have connections with SNRs and/or from which X-ray radiation has been observed, is displayed. As seen from this figure and Table 1, pulsars Geminga and J0538+2817 which is connected to SNR G180.0-1.7 (Romani & Ng 2003) have about one order of magnitude larger values of $\dot{\rm E}$ compared to old ms pulsars, but their luminosity in 2-10 keV band is similar to the luminosity of these ms pulsars. The X-ray spectra of the mentioned young pulsars are steeper compared to the spectra of ms pulsars as seen from the comparison of the luminosities in 0.1-2.4 keV and 2-10 keV bands. The luminosities of J0826+2637 and J0953+0755 in 2-10 keV band are smaller than the luminosities of old ms pulsars, but their $\dot{\rm E}$ values are also smaller (see Figure 3). How can we explain such a situation?

Young pulsars have values of electric field intensity about 50 times larger than the values of old ms pulsars, they are hotter and they may also have smaller masses. These facts create conditions for tearing off charged particles more easily from neutron stars. On the other hand, the magnetic field values of young pulsars are more than 3 orders of magnitude larger (the high magnetic field does not let the particles to escape from the magnetosphere).

These and the possible existence of large number of charged particles in the magnetospheres and the surroundings of young pulsars must create the best conditions for magneto-braking and Coulomb radiation. The small values of X-ray radiation of J0538+2817 and Geminga in 2-10 keV band seem to contradict this natural discussion. We can attempt to get rid of this contradiction if we take into consideration the considerably large values of radiation of the mentioned young pulsars in 0.1-2.4 keV band. The large magnetic field and density of charged particles may create conditions under which the energy loss of particles in 0.1-2.4 keV band surpasses the energy which is received from magnetodipole radiation wave for the further acceleration.

The existence of large number of accelerated particles and high values of magnetic field is well a basis for strong radio radiation. The radio luminosities at 1400 MHz of 4 old ms pulsars are about 1-2 order of magnitude smaller than the radiation of young pulsars as mentioned above. The synchrotron radiation of electrons in unit time is proportional to the value of B. As magnetic field of ms pulsars is $\sim$3 orders of magnitude smaller than the considered young pulsars, the magnetosphere of ms pulsars must contain more than 1 order of magnitude more ultrarelativistic particles compared to the magnetosphere of young pulsars. This comes from the comparison of the intensity of the radio radiation. On the other hand, the maximum radiation at the given frequency is $\sim$BE^2, where E is the electron energy. Therefore, the energy of electrons which is responsible for the radiation at 1400 MHz in the case of ms pulsars is also large. This shows that the acceleration of charged particles takes place in the field of magnetodipole radiation wave and number density of the charged particles, which interact with the accelerated particles, in the atmosphere of ms pulsars is small. So, the cause of the hard X-ray spectra of ms pulsars is understandable.

4 Pulsar wind nebulae and pulsars in supernova remnants

Let us now examine the presence or absence of PWN around pulsars and the X-ray radiation. All the pulsars with $\tau < 10^7$ yr represented in Table 1 are shown in the P-$\dot{\rm P}$ diagram in Figure 4 denoting also the types of the SNRs which some of the pulsars are connected to. If the type of the SNR is C

(composite) or F (filled-centre), then it means that there is PWN created by the neutron star. In S (shell) type SNRs there is no observed PWN possibly because it is very faint. Other pulsars in Table 1 which are not connected to SNRs and which have $\tau < 10^7$ yr are also displayed in Figure 4. All the pulsars with PWN around them have L_x (2-10 keV) $> 10^{33}$ erg/s (see Table 1). The cooling radiation of these pulsars do not have a considerable role.

Pulsars J1952+3252, J2337+6151, and J0659+1414, which are connected to S-type (in radio band) SNRs, have been observed to radiate in X-ray band. Pulsar J1952+3252 has the highest value of L_x (2-10 keV) among these pulsars and one can expect to observe PWN around this pulsar considering also the small distance and the position of it in the Galaxy (see Table 1). On the other hand, the SNR which this pulsar is connected to (CTB 80) is a well known very old SNR. Pulsars J2337+6151 and J0659+1414 have also suitable distance values and positions to observe possible PWNe around them, but $\dot{E}$ and L_x (2-10 keV) values of these pulsars are so small that it is not so likely that PWNe with observable brightness are present around them.

From the analysis of these data, we see that lifetime of the X-ray radiation produced by the relativistic particles in the magnetospheres of neutron stars is longer than lifetime of PWNe (see Table 1). But there may be one exception, namely pulsar J0538+2817, which is connected to SNR G180.0-1.7 (S147). This SNR is S-type in radio band (Green 2001). Romani & Ng (2003) claim evidence for a faint nebula around the pulsar, but in a more recent work (McGowan et al. 2003) no evidence has been found of a PWN and the pulsar has been observed to radiate only thermally. Also, the positions and ages of the pulsar and the SNR show that a physical connection between these two sources is dubious and there are no data directly showing evidence for the connection.

There is another interesting problem: it is known that more energetic particles have shorter lifetime compared to less energetic particles in a PWN. So, one may expect to see the diminishing of the X-ray radiation of PWN long before the diminishing of its radio radiation, i.e. one may expect to observe the PWN in radio band for a much longer time compared to observing the X-ray PWN. We have examined the PWNe both in the radio and the X-ray bands and we have seen that the lifetime of radio PWN is comparable to the lifetime of X-ray PWN based on the up-to-date observational data. So, maybe the ultrarelativistic particles escape from the PWN or the PWN

disrupts shortly after the high-energy partisles in the PWN which produce the X-ray radiation come to the end of their lifetime. Also, the X-ray luminosity of pulsars in 2-10 keV band drops down to $\sim 10^{33}$ erg/s at about the same time when the PWN becomes unobservable both in radio and X-ray bands.

From Figure 4 and Table 1 we see that PWN may exist around pulsars with $\dot{\mathrm{E}}>10^{35}$ erg/s and $\tau<5\times10^{4}$ yr. Pulsar J1646-4346 in C-type SNR G341.2+0.9 satisfies these criteria, but X-ray radiation has not been observed from it because it is located at a distance of 6.9 kpc (Guseinov et al. 2003b). X-ray radiation has not been observed also from 9 far away pulsars with d$\geq$3 kpc which are located close to the Galactic plane in the Galactic central directions (see Table 1 and Figure 4) and which satisfy the conditions of large value of $\dot{\mathrm{E}}$ and small value of τ. As seen from the position of pulsar J1617-5055 in Figure 4, it must have a connection with SNR and must have PWN. This follows also from the large values of X-ray luminosity in both considered bands. Lack of observed SNR and PWN must be related with the large distance and the position in the Galaxy. Ages of the relatively nearby pulsars which are displayed in Figure 4 may be smaller than the values of τ. Three of these pulsars are connected to S-type SNRs and all of them have small X-ray luminosity.

5 Conclusions

From the analysis of all the available data of single X-ray pulsars, their wind nebulae and the SNRs which are connected to some of these sources and also from theoretical considerations we have found the conclusions below:
1. The electric field intensity (voltage) of neutron stars is not the main physical quantity for the spectra, energy, and intensity of the relativistic particles which produce the X-ray radiation of single pulsars and their wind nebulae. The voltage mainly triggers the acceleration of particles. In order to tear off charged particles from the surface of neutron star E_{el} must be large. This process occurs more easily in hot and extended atmospheres. Therefore, the values of mass and age of pulsars also have important roles in the formation of the X-ray radiation.
2. The acceleration of relativistic particles mainly takes place in the field of the magnetodipole radiation wave. Because of this, the X-ray radiation of pulsars and their wind nebulae strongly depend on the value of rate of

rotational energy loss which is reflected by the spectra of the magnetodipole radiation.
3. The high magnetic field and particularly the number density of the charged particles create conditions under which the energy loss of the particles in 0.1-2.4 keV band may surpass the energy received from the magnetodipole radiation wave for further acceleration. This must be responsible for the steeper X-ray spectra of young pulsars as compared to ms pulsars.
4. PWN exists only around pulsars with $\dot{E}>10^{35}$ erg/s and $\tau<5\times10^{4}$ yr. Also, the X-ray luminosity of pulsars in 2-10 keV band drops down to $\sim10^{33}$ erg/s at about the same time when the PWN becomes unobservable in both radio and X-ray bands. The lifetime of S-type SNRs may exceed the lifetime of F and C-type SNRs. So, it may be possible that C-type SNRs can show themselves as S-type after some time in their evolution. PWN must be observed around pulsar J1617-5055.

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Table 1 - All 33 radio and X-ray pulsars with detected X-ray radiation in 0.1-2.4 keV and/or in 2-10 keV bands and with $\tau<10^6$ yr. All 15 pulsars which have Log $\dot{E}>35.6$ and $\tau<10^5$ yr. All pulsars which are connected to SNRs (PWNe). Two of these pulsars are in Magellanic Clouds and the others are Galactic pulsars with d$\leq$7 kpc. In the first column 'G' denotes strong glitch. In column 12 $\beta=2\Delta\theta/\theta$ (θ: SNR diameter, $\Delta\theta$: angular distance of pulsar from the geometric centre of SNR).

	JName	Type	d kpc	P s	$\dot{P}$ s/s	Log τ	Log B	Log $\dot{E}$	SNR + l,b	Type	β	Log L_x 0.1-2.4 keV	Log L_x 2-10 keV
	J1846-0258	X	6.7	0.325	7.1E-12	2.859	13.70	36.9	G29.7-0.3	C	~0 [1]	~35.18	35.32
	J0534+2200	ROXG	2.0	0.034	4.21E-13	3.10	12.58	38.64	Crab	F	~0.19 [2]	35.98	36.65
	J1513-5908	RXG	4.2	0.151	1.54E-12	3.191	13.19	37.25	G320.4-1.2	C	0.24 [2]	34.25	35.32
	J1119-6127	RX	7.0	0.408	4.02E-12	3.205	13.61	36.37	G292.2-0.5	C	~0 [3]	≤32.5	33.42
	J0540-6919	ROX	50	0.051	4.79E-13	3.22	12.70	38.17	N158A	C	~0 [4]	36.21	36.93
	J1124-5916	RX	6.0	0.135	7.45E-13	3.458	13.01	37.07	G292.0+1.8	C		~32.7	34.67
	J1930+1852	RX	7	0.137	7.51E-13	3.462	13.0	37.23	G54.1+0.3	F		~34.2	
	J0537-6910	RX	50	0.016	5.1E-14	3.7	12.0	38.7	N157B	F		~36.0	36.11
	J0205+6449	RX	3.2	0.066	1.9E-13	3.74	12.55	37.42	G130.7+3.1	F		32.38	34.26
G	J1617-5055	RX	6.2	0.069	1.371E-13	3.903	12.49	37.21	332.5,-0.27			34.30	34.59
	J2229+6114	RXG	5.5	0.052	7.8E-14	4.023	12.31	37.34	G106.6+2.9	C	0 [5]	33.58	33.69
G	J0835-4510	ROXG	0.40	0.089	1.25E-13	4.05	12.53	36.84	Vela	C	0.29,0.3 [2,3]	32.46	33.18
	J1420-6048	RXG	6.1	0.068	8.32E-14	4.113	12.38	37.01	G313.4+0.2?	F	0.2 [6]	34.26	34.30
G	J1801-2451	RX	4.5	0.125	1.28E-13	4.19	12.61	36.41	G5.27-0.9	F	~0 [7]	~33.0	33.18
G	J1803-2137	RX	3.5	0.134	1.34E-13	4.197	12.63	36.35	G8.7-0.1	S?	0.7 [8]	33.06	32.39
	J1702-4310	R	4.8	0.2405	2.24E-13	4.23	12.88	35.80	343.4,-0.85				
G	J1709-4428	RXG	1.8	0.102	9.30E-14	4.241	12.49	36.53	G343.1-2.3?			33.15	32.58
	J1856+0113	RX	2.8	0.267	2.08E-13	4.31	12.88	35.63	G34.7-0.4	C	0.51[2],0.6[3]	≤33.0	33.03
	J1048-5832	RXG	2.8	0.124	9.63E-14	4.31	12.54	36.30	287.4,+0.58			≤32.11	32.35
	J1016-5857	RX	6.5	0.107	8.11E-14	4.321	12.48	36.41	G284.3-1.8	S	1[6],1.3[9]	~33.5	
G	J1826-1334	RX	3.4	0.101	7.55E-14	4.33	12.45	36.45	G18.0-0.7	F		~32.7	34.34
	J1811-1925	X	5	0.065	4.22E-14	4.4	12.23	36.78	G11.2-0.3	F	~0 [10]	32.8	34.54
	J1747-2958	RX	2.0	0.099	6.14E-14	4.41	12.41	36.41	G359.2-0.8?	F		~34.0	
G	J1730-3350	R	4.24	0.1394	8.51E-14	4.41	12.56	36.09	354.1,+0.09				
	J1646-4346	R	6.9	0.232	1.13E-13	4.51	12.71	35.55	G341.2+0.9	C	0.7 [8]		
	J1837-0604	R	6.2	0.0963	4.52E-14	4.53	12.34	36.30	26.0,+0.27				
	J1015-5719	R	4.87	0.1399	5.74E-14	4.59	12.47	35.92	283.1,-0.58				
	J2337+6151	RX	2.8	0.495	1.92E-13	4.611	12.99	34.79	G114.3+0.3	S	0.08 [2,11]	31.90	31.47
	J1637-4642	R	5.5	0.1540	5.92E-14	4.62	12.50	35.81	337.8,+0.31				
	J0940-5428	R	3.8	0.0875	3.29E-14	4.63	12.25	36.29	277.5,-1.29				
	J0631+1036	RX	6.6	0.288	1.05E-13	4.639	12.74	35.24	201.2,+0.45				31.90
	J1809-1917	R	3.3	0.0827	2.55E-14	4.71	12.18	36.25	11.1,+0.08				
	J1105-6107	RX	7.0	0.063	1.58E-14	4.801	12.01	36.39	290.5,-0.85			~33.2	33.55
	J1718-3825	R	3.3	0.0747	1.32E-14	4.95	12.02	36.10	348.9,-0.43				
	J1531-5610	R	2.6	0.0842	1.37E-14	4.99	12.05	35.96	323.9,+0.03				
	J1952+3252	RXG	2.0	0.040	5.84E-15	5.030	11.69	36.57	G69.0+2.7	?	0.14,0.15[2,3]	33.64	33.07
	J0659+1414	ROX	0.6	0.385	5.50E-14	5.044	12.67	34.58	G201.1+8.7			32.78	30.92
	J0908-4913	R	4.5	0.1068	1.51E-14	5.05	12.12	35.69	270.3,-1.02				
	J0855-4644	R	6.4	0.0647	7.26E-15	5.15	11.85	36.03	267.0,-1.0				
G	J1833-0827	R	5.67	0.0853	9.17E-15	5.17	11.97	35.77	23.4,+0.06				
	J1509-5850	R	2.5	0.0889	9.17E-15	5.19	11.97	35.71	320.0,-0.62				
	J1913+1011	R	4.1	0.0359	3.37E-15	5.23	11.56	36.46	44.5,-0.17				
	J0117+5914	RX	2.4	0.101	5.85E-15	5.44	11.89	35.34	126.3,-3.46				30.44
Be	J1302-6350	RX	1.3	0.048	2.28E-15	5.52	11.52	35.92	304.2,-1.00			32.95	32.57
	Geminga	X	0.15	0.237	1.14E-14	5.53	12.22	34.53	195.13,+4.27			31.10	29.33
	J1057-5226	RX	1.0	0.197	5.83E-15	5.73	12.04	34.48	286.0,+6.65			33.13	30.08
G	J0358+5413	RX	2	0.156	4.4E-15	5.75	11.92	34.66	148.2,+0.81			31.96	31.75
	J0538+2817	RX	1.5	0.143	3.67E-15	5.79	11.87	34.69	G180.0-1.7?	S		32.74	29.31

Table 1 - continued

JName	Type	d	P	$\dot{P}$	Log τ	Log B	Log $\dot{E}$	SNR + l,b	Type	β	Log L_x	Log L_x
		kpc	s	s/s							0.1-2.4 keV	2-10 keV
1932+1059	RX	0.2	0.227	1.16E-15	6.49	11.71	33.59	47.38,-3.88			30.07	29.41
0826+2637	RX	0.4	0.531	1.71E-15	6.69	11.98	32.65	196.96,+31.74			31.85	29.01
0953+0755	RX	0.13	0.253	2.29E-16	7.24	11.39	32.75	228.91,+43.7			29.35	28.62
1824-2452	RX	5.1	0.003	1.62E-18	7.48	9.35	36.35	7.8,-5.58			32.2	33.56
1939+2134	RX	3.6	0.0015	1.06E-19	8.37	8.61	36.04	57.51,-0.29			<32.1	32.54
2124-3358	RX	0.25	0.005	2.0E-20	9.58	8.51	33.83	10.93,-45.44			30.35	29.58
1024-0719	RX	0.35	0.005	1.9E-20	9.64	8.50	33.73	251.7,+40.52			29.48	29.09
0030+0451	RX	0.23	0.005	1.0E-20	9.89	8.35	33.53	113.14,-57.61			30.56	29.88
1744-1134	RX	0.36	0.004	8.9E-21	9.86	8.29	33.72	14.79,+9.18			29.58	29.25

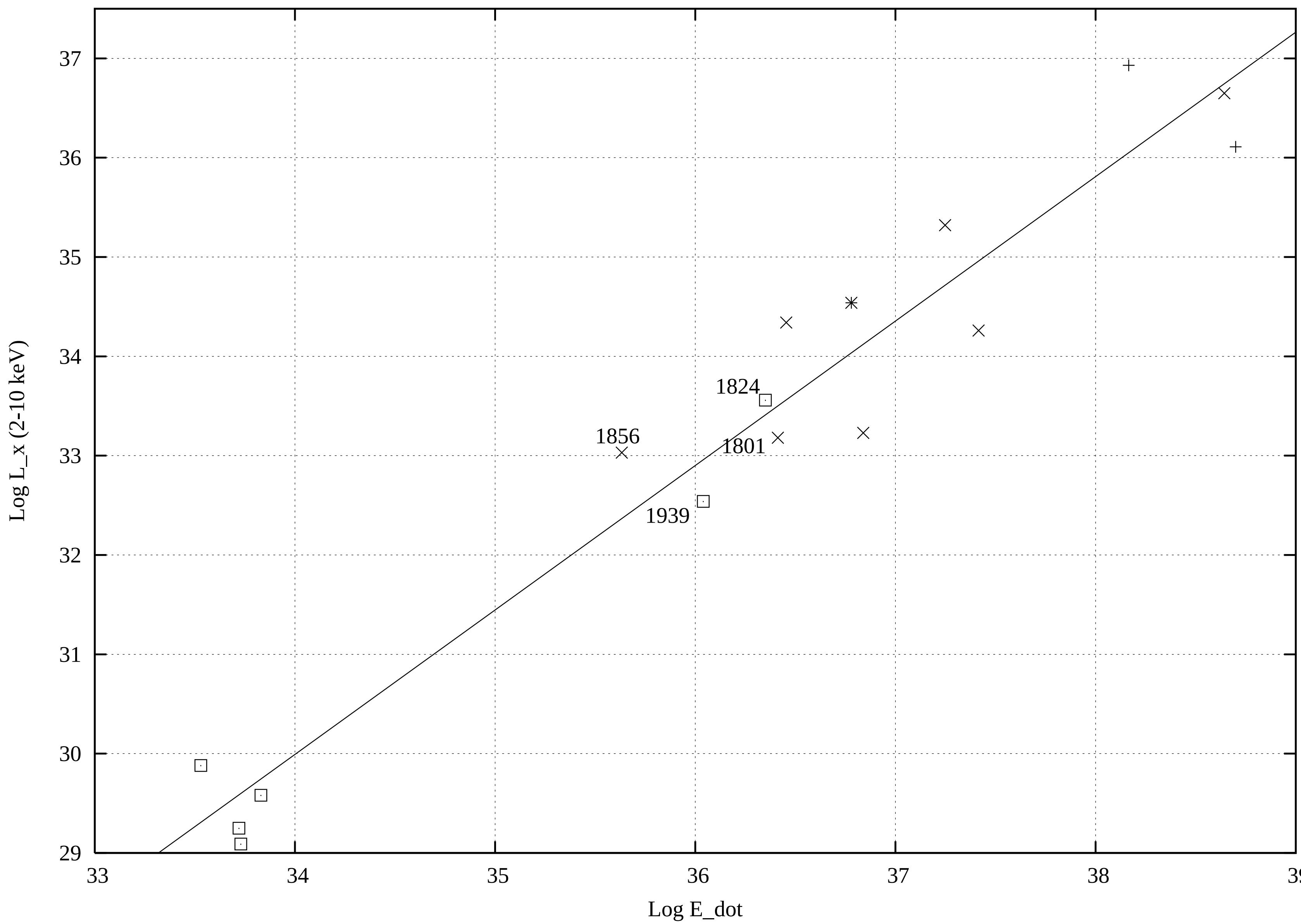
[1] Helfand et al. 2003; [2] Lorimer et al. 1998; [3] Allakhverdiev et al. 1997; [4] Seward et al. 1984; [5] Kothes et al. 2001; [6] Manchester et al. 2002; [7] Thorsett et al. 2002; [8] Frail et al. 1994; [9] Camilo et al. 2001; [10] Kaspi et al. 2001; [11] Furst et al. 1993.

Figure Captions

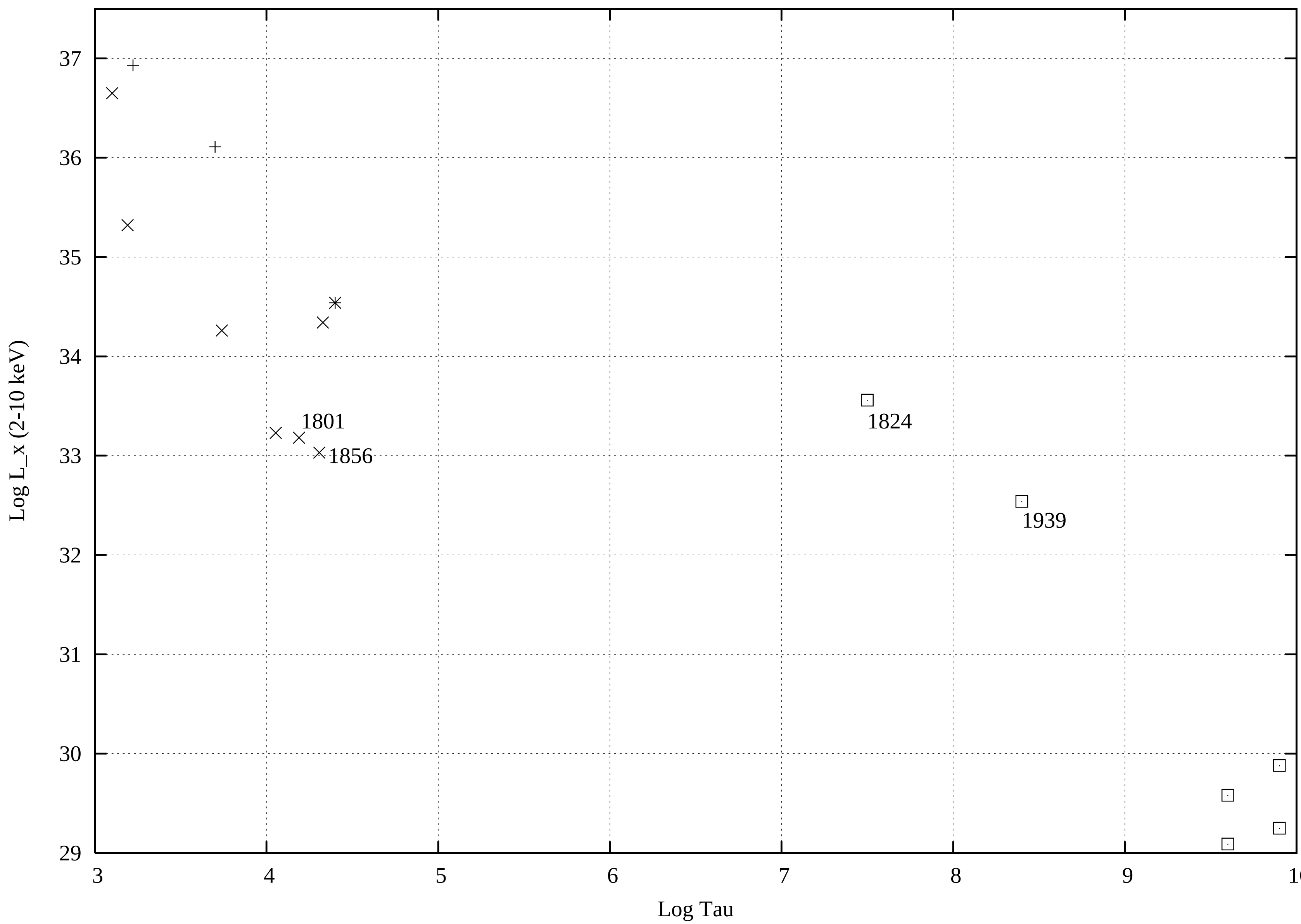
Figure 1: Dependence of the 2-10 keV luminosity on the rate of rotational energy loss for pulsars located up to 5 kpc from the Sun including also 2 pulsars in Magellanic Clouds which are denotes with '+' sign. The single strong X-ray pulsar from which no radio radiation has been detected is represented with sign 'star'. Pulsars with $\tau < 10^5$ yr are shown with 'X' sign. The old millisecond pulsars are displayed with 'square'.

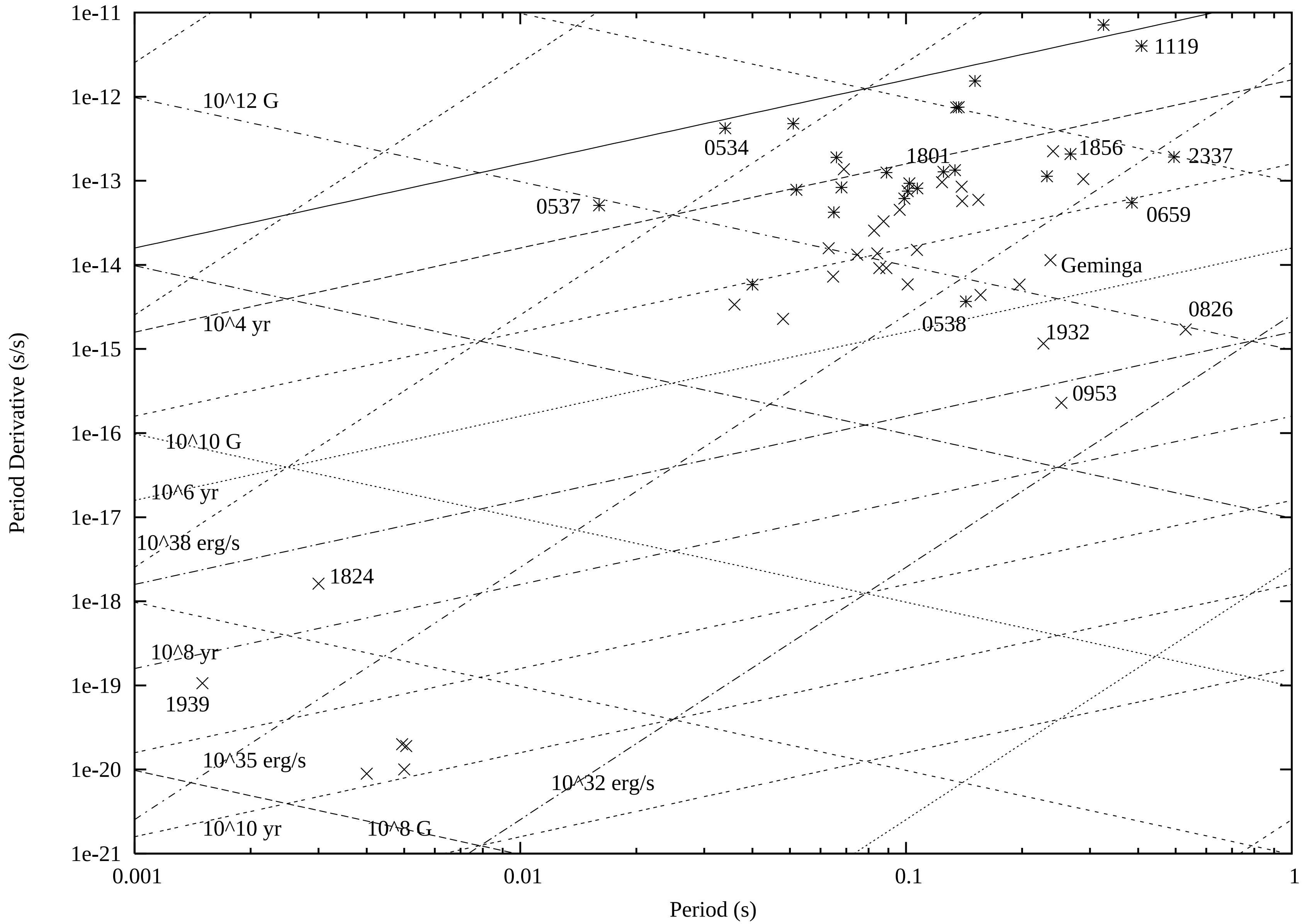
Figure 2: Dependence of the 2-10 keV luminosity on characteristic time for pulsars located up to 5 kpc from the Sun including also 2 pulsars in Magellanic Clouds. The pulsars are denoted with the same symbols as in Figure 1. **Figure 3:** Period versus period derivative diagram for the pulsars which have been detected in X-ray and/or which are connected to SNRs (see Table 1). The sign 'star' represents the pulsars which have genetic connections with SNRs and the 'cross' sign denotes the pulsars which are not connected to SNRs.

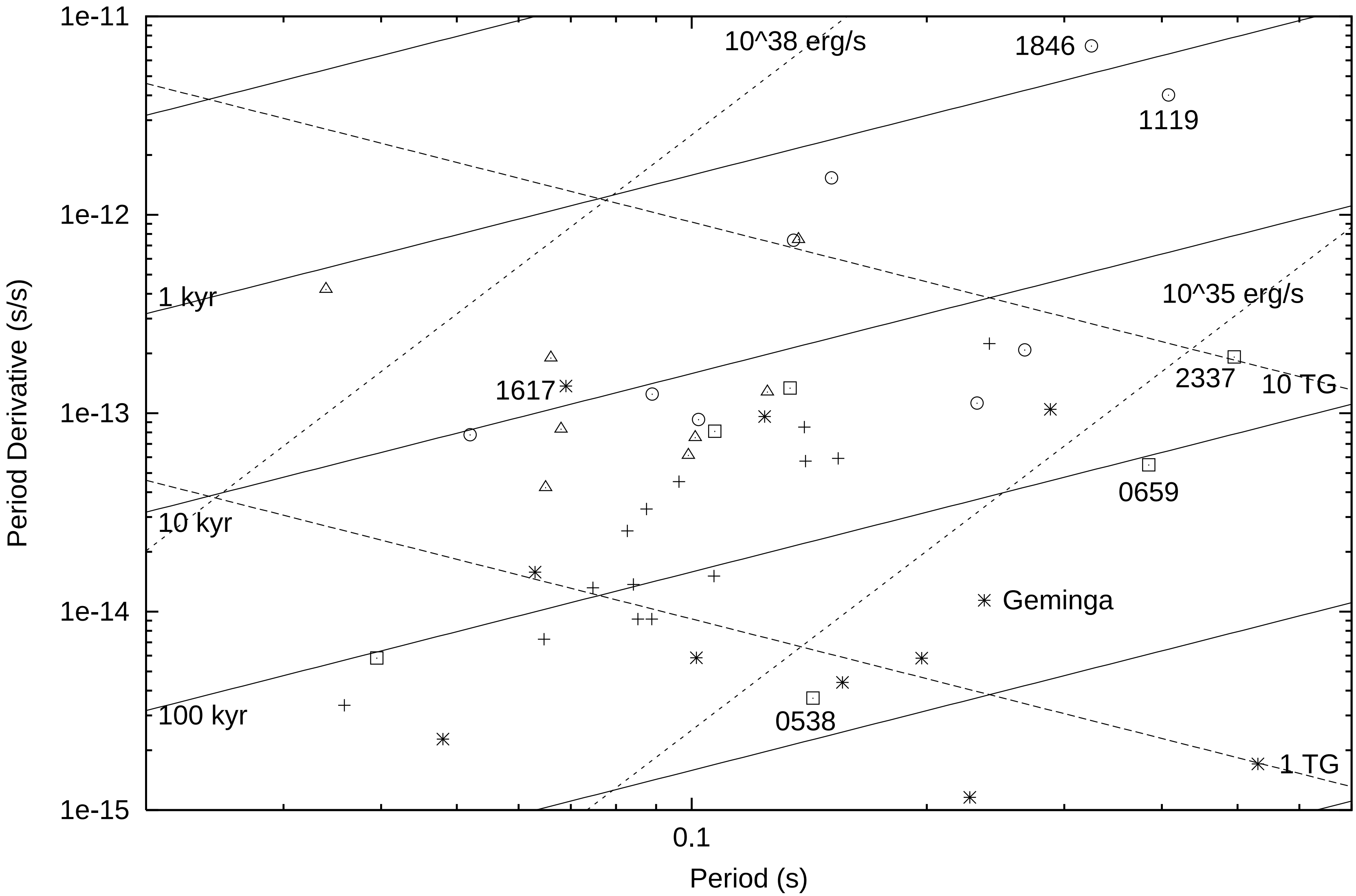
Figure 4: Period versus period derivative diagram for all 48 pulsars represented in Table 1 with $\tau < 10^6$ yr and distance ≤ 7 kpc including the 2 pulsars in Magellanic Clouds. 'Circles' represent the 11 pulsars connected to C-type SNRs, 'triangles' show the 9 pulsars connected to F-type SNRs, and 'squares' denote the 3 pulsars connected to S-type SNRs. 'Plus' signs represent the 14 pulsars which are not connected to SNRs and not observed in X-ray. The 11 pulsars which are denoted with 'stars' have been observed in X-ray but they are not connected to SNRs.



Log L_x (2-10 keV)
Log E_dot
29
30
31
32
33
34
35
36
37
33
34
35
36
37
38
39
1824
1856
1801
1939


Log L_x (2-10 keV)
37
36
35
34
33
32
31
30
29
1801
1856
1824
1939
3
4
5
6
7
8
9
10
Log Tau


Period Derivative (s/s)
Period (s)
1e-11
1e-12
1e-13
1e-14
1e-15
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
0.001
0.01
0.1
1
10^12 G
10^10 G
10^8 G
10^4 yr
10^6 yr
10^8 yr
10^10 yr
10^38 erg/s
10^35 erg/s
10^32 erg/s
1119
0534
1801
1856
2337
0537
0659
Geminga
0826
0538
1932
0953
1824
1939


1e-11
1e-12
1e-13
1e-14
1e-15
0.1
Period (s)
Period Derivative (s/s)
10^38 erg/s
10^35 erg/s
1 kyr
10 kyr
100 kyr
10 TG
1 TG
1846
1119
1617
2337
0659
Geminga
0538